INJECTION OF ENERGETIC PARTICLES FOLLOWING THE GAMMA-RAY FLARES ON JUNE 7 , 1980, AS OBSERVED ON HELIOS-1.

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ABSTRACT

On June 7, 1980, two flares with impulsive gamma-ray emission were observed at 0117 UT and 0312 UT. We present measurements of the University of Kiel cosmic-ray experiment on HELIOS-1. The first ∿0.5 MeV electrons escaped from the sun to interplanetary space simultaneously with the hard X-ray burst. For the 0312 UT flare the protons and α-particle in the 3 - 20 MeV/nucleon range were injected from the sun with a delay of ∿40 min, followed by two subsequent new emissions.

1. Introduction. For a long time it was postulated in most models that the ion and relativistic electron acceleration takes place in the "second phase" of a flare, some ten seconds after the impulsive phase. But gamma-ray observations on SMM demonstrated (1) that these particles can be accelerated very rapidly and appear almost simultaneously with the non-relativistic electrons within time scales of seconds.

Correlations between the emission of hard electromagnetic radiation and the escaping energetic charged particles should give important clues for the acceleration mechanism. However, first studies showed that the number of nucleons escaping into space is only a small fraction of the number required to explain the observed gamma emission (2). A lack of correlation was found between the nuclear gamma emission of the flare and the size of the interplanetary proton events (3). These observations were explained by a highly variable ratio of particles moving upwards and downwards after acceleration, or by the existence of two independent populations.

In this paper we study the injection of energetic electrons, protons, and helium nuclei following a series of flares on June 7, 1980. The small distance of the HELIOS spacecraft to the sun and the unusually smooth interplanetary magnetic field allow a temporal resolution of the solar injection process which has not been reached before.

2. Observations. Energetic particle data were obtained with the University of Kiel cosmic ray experiment on HELIOS-1 (4,5). The instrument measures electrons with energies $\gtrsim$ 0.3 MeV, nucleons above 1.3 MeV/N in eight sectors each 45^o wide in the ecliptic plane. For selected energy channels pulse height analysis allows particle identification and precise energy measurement for a representative sample of all incoming particles.

HELIOS-1 was in an ideal position to study the solar events on June 7, 1980, which occurred in Hale plage region 16886. The spaceprobe was located at 0.37 AU distance from the sun and was magnetically connected to a coronal region about 2 - 11^o apart from the active region. Solar wind data indicate that HELIOS-1 was inside a "hole" in the solar wind (Schwenn, private communication). The interplanetary magnetic field (courtesy F.M. Neubauer, G. Musmann) was exceedingly smooth. As a consequence, solar energetic particles arrive totally collimated and were practically confined to the sector which contained the magnetic field direction leading towards the sun. This allows to reduce the isotropic background considerably and to reconstruct directly the injection profile at the sun.

Figure 1 shows three minute averages of the particle intensities from the solar oriented sector for a 12 hour period on June 7. Time and location of the three solar flares are given in the inserts in the upper panel. The first two flares are also observed at $\gtrsim$ 0.3 MeV gamma energies, the third one is not. It is remarkable that this event shows the largest intensity in electrons. Because of the scatter free interplanetary propagation we can directly construct the total number of injected particles by integrating the observed directional intensities over time. The total electron numbers for the three events vary as 1:6:29. In contrast, the X-ray emission in the 1.6 to 12.4 keV range varies as 1:3:0.2.

In Figure 2 we have corrected for the interplanetary travel time of each particle group by subtracting $t = s/v$ from the time of observation. Here s is the curved path length along the smooth interplanetary magnetic field spiral, as determined from the measured solar wind speed. The velocity v is determined from identification and energy measurements of the various particles. Results are plotted as a function of "solar release time" (SRT). Earth bound electromagnetic observations have been corrected accordingly. On this scale, the emission of electrons and X-rays occurs simultaneously, whereas for the first two flares the protons are delayed. In case of the 0315 flare we also find a multiple injection, with the first proton injection starting at 0345 SRT, the second at 0440 SRT. The last release at 0635 SRT is superimposed by a fresh injection of particles from the 0725 flare. In this case, protons and electrons are injected simultaneously and also coincident with the optical flare.

The temporal relation between X-ray and electron emission for the three flares is shown on an extended time scale in Figure 3. It shows that within about one minute the electron injection onset matches the impulsive X- and gamma-ray emission of the flare which marks the particle acceleration. The number of injected electrons has reached their maximum (I_{max}) in several minutes, but the injection lasts in any case much longer than the electromagnetic emission (see Figure 2). The steps in the electron onset in Figure 3 correspond to the temporal resolution of the data transmission of HELIOS at the time of observation. The uncertainty in fixing the release time by uncertainties in the path length is below one minute.

Figure 4 shows the injection of nucleons of different energy/nucleon, ordered from top to bottom with decreasing velocity. For the three separate injections following the 0315 flare we find that higher energy nucleons are injected later. This inverse velocity dispersion is not observed for the 0725 flare. Here nucleons are released simultaneously with the electrons.

Energy spectra can be fitted by power laws in kinetic energy over the range of observation (see Table 1). The electrons resulting from the gamma-flares show a harder spectrum. This is in accordance with results in (6). We see that also the proton energy spectrum for the 0725 flare which was not accompanied by gamma-rays is steeper than the first injections for the other cases. For the three consecutive injections following the 0315 flare the spectrum steepens from one injection to the next.

In summary, we find the following observations:

(1) The $\sim$0.5 MeV electrons are released simultaneously with the hard X-ray bursts for all three events, within the temporal uncertainty of about one minute.
(2) The electron injection continues for 15 - 20 minutes, much longer than the duration of the X-ray bursts.
(3) There is no correlation between the number of electrons in interplanetary space and the emission in 1 - 8 Å X-rays or $\gtrsim$ 0.3 MeV gamma-rays.
(4) For the flares at 0118 and 0315 nucleons are released from the sun with a considerable delay.
(5) We find repeated injections of nucleons after the 0315 flare. For each of the three subsequent injections the proton spectrum gets steeper.
(6) After correcting for interplanetary travel times we find that the injection starts later for nucleons of higher energy/nucleon.

3. Discussion. The delayed emission of nucleons confirms the view that the nucleons observed in interplanetary space need not be identical with the component responsible for the gamma-ray generation. Nevertheless the emitted nucleons may have been accelerated simultaneously with a gamma producing component, followed by storage in closed magnetic field regions with subsequent repeated release, possibly connected to the bird cage model (7). However, in this model the immediate release of electrons would be hard to understand. An alternate explanation for two independent populations is the acceleration of nucleons by a coronal shock wave. A type-II radio burst suggestive for a coronal shock had been observed after the 0312 flare, but not for the 0725 flare. In this event not accompanied by gamma-ray production the release of electrons and nucleons occurs simultaneously.

4. Acknowledgements. We are grateful to all members of the HELIOS team at the University of Kiel, principal investigator H. Kunow, who contributed to the success of the cosmic ray experiment. Unpublished X-ray data from the SMM gamma-ray experiment (see Figure 3) have been kindly supplied by E. Rieger, Garching. This work was supported by the German Bundesminister für Forschung und Technologie.

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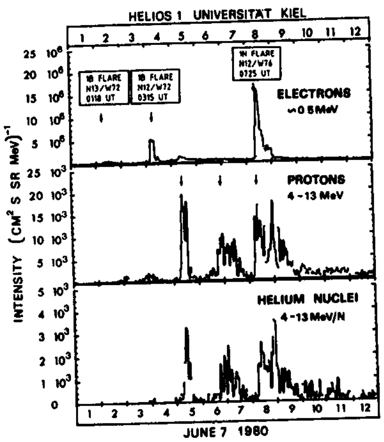

Figure 1: Particle intensities from the solar direction on a linear scale.

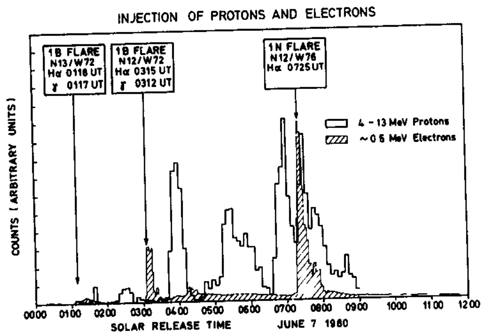

Figure 2: Solar injection of electrons and protons after correction for interplanetary travel time along the smooth interplanetary magnetic field. Solar Release Time (SRT)= UT - s/v.

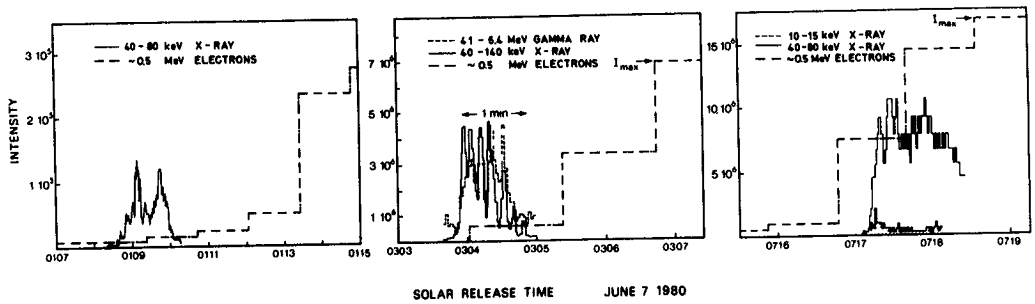

Figure 3: Temporal correlation between hard electromagnetic radiation and the release of relativistic electrons.

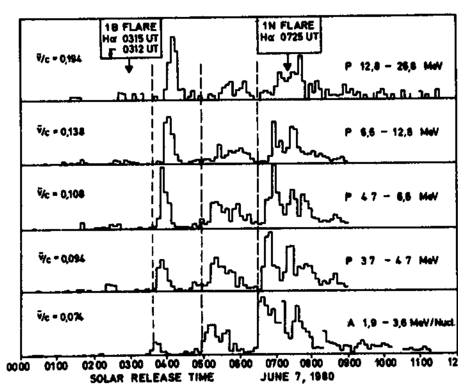

Figure 4: Energy dependence of solar release of protons (P) and Helium nuclei (A). The energy range is indicated on the right side. The dashed vertical lines give the injection onset for the lowest velocity channel.

Particle type	time interval	spectral index
electron (0 3 to 4 MeV)	0113 - 0154 UT 0307 - 0330 UT 0720 - 0804 UT	3 50 ± 0 11 3.48 ± 0.07 3.93 ± 0.05
proton (4 to 37 MeV)	0138 - 0317 UT 0416 - 0449 UT 0513 - 0646 UT 0712 - 0745 UT 0745 - 0858 UT	2.29 ± 0.25 2 67 ± 0 13 3 04 ± 0 15 3 66 ± 0 24 3 18 ± 0 13

Table 1: Spectral indices for a power law fit of the measured spectra. Proton spectra: The second to fourth time interval represent the three injections following the 0315 flare.